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for

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Air Force Office of Scientific Research
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A finite element computer code is under development which is specialized to strong nonlinearities of the geometrical type. The work includes beam and shell elements, and makes use of three important technical features to best address the nonlinear problem. These are: (1) the use of higher degree functions for the membrane or axial displacements than for the bending displacements: (2) the use of the static perturbation method; (3) the use of Euler angles to represent rotations. Computed results illustrate the methods and computer codes developed.

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ABSTRACT

A finite element computer code is under development which is specialized to strong nonlinearities of the geometrical type. The work includes beam and shell elements, and makes use of three important technical features to best address the nonlinear problem. These are: (1) the use of higher degree functions for the membrane or axial displacements than for the bending displacements; (2) the use of the static perturbation method; (3) the use of Euler angles to represent rotations. Computed results illustrate the methods and computer codes developed.

The objective of this contract is the development of a static and dynamic analysis approach applicable to finite element structural analysis in which strong geometrical nonlinearities result from large deflection behavior. The approach is to include curved beam elements and doubly curved shell elements, and it is to incorporate new technical approaches in at least two areas: (1) element axial/membrane displacement functions are to use a higher degree polynomials than the bending functions; (2) the static perturbation solution procedure is to be used for both the static and dynamic applications. This work follows previous contracts dealing with special finite element techniques for dealing with strong geometrical nonlinearities, primarily pertaining to item (1) above. In the earlier work a number of solution procedure refinements were developed for the purpose of accelerating convergence of the iterative nonlinear solution process. These included algorithms controlling the updating of element deformed geometries and of element stiffness matrices; the selection of a subset of particular freedoms of the structure to be incremented in the iteration process, such that solution errors are minimized and convergence accelerated; and automatic scaling of the magnitudes of iteration increments in order to accelerate convergence. The current research will make use of these techniques where improved code performance can be obtained thereby, and will determine to what extent the use of the static perturbation method suffices to make some of the previous solution procedure refinements unnecessary. An additional refinement to be investigated in the present research is automatic rezoning of the finite element mesh, in order to assure a modeling which is well adapted to particular structural and nonlinear characteristics of the problem being solved.

The work to date has completed a demonstration computer code for curved beam elements deforming in a single plane (hereafter called "2D BEAM" elements). This code uses the particular types of displacement functions and the static perturbation process which are the primary goals of the research. It incorporates a variety of solution procedure options, including those from previous contracted work, which are being tested both in comparison with, and in conjunction with, the static perturbation method. These options include:

(1) geometrical updating; (2) stiffness matrix updating; (3) use of, or omission of, the static perturbation method; (4) automatic optimization of the static perturbation "path parameter" within the calculations; (5) choice of second-order or third-order static perturbation calculations; (6) selective freedom iteration (membrane/axial-only, versus all-freedom iteration) both in conjunction with, and instead of, the static perturbation approach.

The theory and code (2D BEAM) use a special element nodal arrangement in which each element has three nodes (one internal) for describing bending deformations and five nodes (3 internal) for describing axial deformations. This arrangement results in a quadratic bending displacement shape and a quartic axial displacement shape. These particular polynomial forms are sufficient to eliminate the effect of "nonlinear stiffening" of the finite element due to the differing, unbalanced deformation patterns of the linearly-induced, as opposed to the nonlinearly-induced, axial deformations. Handling this problem, which is characteristic of strongly nonlinear finite element analysis, is the purpose of using the special types of displacement functions under study in this research.

The procedure under study for automatically choosing the static perturbation method path parameter is as follows: in the Taylor series expansion for the displacement increment, ΔQ, keeping terms through the second order,

$$\Delta Q = \dot{Q}_0 S + \frac{1}{2} \ddot{Q}_0 S^2$$

S is the path parameter and $(\dot{\ })$ refers to an S-differentiation. The definition of S is arbitrary, and has been found to have a considerable influence on iteration convergence. It is a reasonable assumption that convergence will be improved if S is chosen such that $\ddot{Q}_0$ is as small as possible. The basis of the assumption is that the error due to series truncation becomes smaller as the primary term in the Taylor series becomes the first, or linear, term. It is possible to determine S by imposing an average "minimization" over the vector $\ddot{Q}_0$. The details of this calculation are omitted here in the interests of simplicity. This approach has been tested in the 2D BEAM code and found to provide much better iteration convergence than other definitions of S, for the second order static perturbation case. An extension of this work to the third order case, in which the $\dddot{Q}_0$ term is retained, is underway.

Also completed to date is the theoretical development of the curved beam element for the case of combined bending and twisting in three dimensions (called herein 3D BEAM). This 3D BEAM derivation will be simply extendable to the case of the shell elements, so that their derivation should be easily accomplished after the 3D BEAM theory is tested in calculations. A particularly complicated technical development is common to the strongly geometrically nonlinear theory for plates, shells, and 3D-beams used in this work. This development concerns the proper handling of rotations, which for large rotations cannot be represented vectorially. Because of this, the incrementation of cartesian, vectorial rotation components imposes cumulative incorrect bending and shearing deformations on the elements. The rigorous approach to this problem is to represent rotations by means of Euler-angles. The Euler angles are a sequenced set of finite rotations about convected, skewed axes, which achieve complete definition of a large rotation state. The necessary developments have been completed for the three-dimensional beam theory. These are usable for plate and shell theory without significant changes or extensions.

To accomplish this has required the development of a new approach and new types of transformations for incremental deformation calculations. The basic problem is the need to account for the transformation between cartesian, vectorial rotation rates and the sequenced Euler angle rates. A corollary problem is the need to define and track two types of local, nodal coordinate systems. One of these is "attached" to the material and becomes a skewed system as the deformation develops; the other remains orthogonal and represents the "beam theory" cross-section axes throughout the deformation, exclusive of the transverse shear deformation angles.

MASIS PROGRESS

The objective of this contract is the development of a static and dynamic analysis approach applicable to finite element structural analysis in which strong geometrical nonlinearities result from large deflection behavior.

The demonstration computer code for curved beam elements deforming in a single plane (hereafter called "2D BEAM" elements) has been completed. This code uses the particular types of displacement functions and the static perturbation process which are the primary goals of the research. It incorporates a variety of solution procedure options, including those from previous AFOSR research, which are being tested both in comparison with, and in conjunction with, the static perturbation method.

The procedure under study for automatically choosing the static perturbation method path parameter is described by a Taylor series expansion for the displacement increment. The definition of the path parameter is arbitrary, and has been found to have a considerable influence on the rate of convergence.

Also completed to date is the theoretical development of the curved beam element for the case of combined bending and twisting in three dimensions (called herein 3D BEAM). This 3D BEAM deviation will be rather simply extendable to the case of the shell elements, so that their derivation should be easily accomplished after the 3D BEAM theory is tested in calculations. This development concerns the proper handling of rotations, which for large rotations cannot be represented vectorially. The rigorous approach to this problem is to represent rotations by means of Euler-angles. To accomplish this has required the development of a new approach and new types of transformations for incremental deformation calculations.

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